
The Rate of Planet Formation and the Solar System's Small Bodies

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ABSTRACT

The evolution of random velocities and the mass distribution of pre-planetary body at the early stage of accumulation are currently under review. Arguments have been presented for and against the view of an extremely rapid, runaway growth of the largest bodies at this stage with parameter values of $\Theta \gtrsim 10^3$. Difficulties are encountered assuming such a large Θ : (a) bodies of the Jovian zone penetrate the asteroid zone too late and do not have time to hinder the formation of a normal-sized planet in the asteroidal zone and thereby remove a significant portion of the mass of solid matter and (b) Uranus and Neptune cannot eject bodies from the solar system into the cometary cloud. Therefore, the values $\Theta < 10^2$ appear to be preferable.

INTRODUCTION

By the beginning of the twentieth century, Ligondes, Chamberlain, and Multan had suggested the idea of planet formation via the combining (accumulation) of solid particles and bodies. However, it long remained forgotten. It was only by the 1940s that this idea was revived by O.Yu. Schmidt, the outstanding Soviet scientist and academician (1944, 1957). He initiated a systematic study of this problem and laid the groundwork for contemporary planet formation theory. He also suggested the first formula for the rate of mass increase of a planet which is absorbing all the bodies colliding with it. After it was amended and added to, this formula took on its present form (Safronov 1954, 1969):

$$\frac{dm}{dt} = \pi r^2 \rho v \left(1 + \frac{2Gm}{v^2 r} \right) = \frac{4\pi r^2 \sigma (1 + 2\Theta)}{P}, \quad (1)$$

where m and r are the mass and radius of the accreting planet, P is its period of revolution around the Sun, ρ and σ are the volume and surface density of solid matter in a planet's zone, and Θ is the dimensionless parameter characterizing random velocities of bodies in a planet's zone (in relation to the Kepler circular velocity of a preplanetary swarm's rotation):

$$v = \left(\frac{Gm}{\Theta r} \right)^{1/2} \propto r \Theta^{-1/2}. \quad (2)$$

However, Schmidt did not consider the increase of a planet's collisional cross section as a result of focusing orbits via its gravitational field, and the factor $(1 + 2\Theta)$ in his formula was absent. For an independent feeding zone of a planet, the surface density σ at a point in time t is related to the initial surface density σ_0 by the simple ratio:

$$\sigma = \sigma_0 (1 - m/Q), \quad (3)$$

where Q is the total mass of matter in a feeding zone of m . It is proportional to the width of the zone $2\Delta R_f$ and is determined, when Θ is on the order of several units, by eccentricities of the orbits of bodies, that is, by their velocities v ; when $\Theta \gg 1$, it is determined by the radius of the sphere of the planet's gravitational influence. In both cases it is proportional to the radius of an accreting planet r . (Schmidt took Q to be equal to the present mass of a planet.)

It is clear from (1) and (2) that relative velocities of bodies in the planet's zone are the most significant factor determining a planet's growth rate. The characteristic accumulation time scale is $\tau_a \propto \Theta^{-1} \propto v^2$. Investigations have shown that velocities of bodies are dependent primarily upon their distribution by mass. Velocities of bodies in the swarm rotating around the Sun increase as a result of the gravitational interactions of bodies and decrease as a result of their inelastic collisions. In a quasistationary state, opposing factors are balanced out and certain velocities are established in the system. If the bulk of the mass is concentrated in the larger bodies, expression (2) for the velocities is applicable for velocities with a parameter Θ on the order of several units. In the extreme case of bodies of equal mass, $\Theta \approx 1$. If the bulk of mass is contained in smaller bodies, an average gravitating mass is considerably less than the mass m of the largest body. The parameter Θ in expression (2) then increases significantly. The velocities of bodies, in turn, influence their mass distribution. Therefore, we need investigations of the coupled evolution of both distributions to produce a strict solution to the problem. This problem cannot be solved

analytically. We thus divided it into two parts: (1) relative velocities of bodies were estimated for a pre-assigned mass distribution, and (2) the mass spectrum was determined for pre-assigned velocities. At the same time, we conducted a qualitative study of the coagulation equation for preplanetary bodies. This effort yielded asymptotic solutions in the form of an inverse power law with an exponent q :

$$n(m) = cm^{-q}, \quad (4)$$

($1.5 < q < 2$) which is valid for all values m except for the largest bodies. Stable and unstable solutions were found and disclosed an instability of solutions where $q > 2$ was noted. In this case, the system does not evolve in a steady-state manner. Then the velocities of bodies assumed a power the law of mass distribution (3) with $q < 2$. They are most conveniently expressed in the form (2). Then $\Theta \approx 3 \div 5$ was found for the system without the gas. In the presence of gas, the parameter Θ is two to three times greater for relatively small bodies.

The most lengthy stage was the final stage of accumulation at which the amount of matter left unaccreted was significantly reduced. There was almost no gas remaining at this stage in the terrestrial planet zone. We found from Expression (1) that with $\Theta = 3$ the Earth ($\sigma_o \approx 10 \text{ g/cm}^2$) accreted about 99% of its present mass in a $\approx 10^8$ year period. The other terrestrial planets were also formed during approximately the same time scale. The time scale of this accumulation process has been repeatedly discussed, revised, and again confirmed for more than 20 years. It may seem strange, but this figure remains also the most probable at this time.

The situation in the region of the giant planets has proven much more complex. From eq.(1) we can find an approximate expression for the time scale T formation of the planet, assuming $\bar{\sigma} \approx \sigma_o/2$. Thus,

$$T \approx \frac{\delta r P}{\Theta \sigma_o}, \quad (5)$$

where δ is the planet density. Current masses of the outer planets (Uranus and Neptune) correspond to $\sigma_o \approx 0.3$, that is, to a value about 30 times less than in the Earth's zone. The periods of revolution of these planets around the Sun $P \propto R^{3/2}$ are two orders of magnitude greater than that of the Earth's. Therefore, with the same values for Θ (cited above), the growth time scale of Uranus and Neptune would be unacceptably high: $T \sim 10^{11}$ years. Of course, this kind of result is not proof that the theory is invalid. It does, however, indicate that some important factors have not been taken into account in that theory. In order to obtain a reasonable value for T , we must increase product $\Theta \sigma_o$ in (5) several dozen times. More careful consideration has shown that such an increase of $\Theta \sigma_o$ has real grounds.

According to (2), velocities of bodies should increase proportionally to the radius of the planet. It is easy to estimate that when Uranus and Neptune grew to about one half of the Earth's mass (i.e., a few percent of their present masses), velocities of bodies for $\Theta = \text{const} \approx 5$ should have already reached the third cosmic velocity, and the bodies would escape the solar system. Therefore, further growth of planet mass occurred with $v = \text{const}$, and consequently, according to (2), Θ must have increased. With the increase of m , the rate of ejection of bodies increased more rapidly than the growth rate of the planet. To the end of accumulation it exceeded the latter several times, the parameter Θ began increased about an order of magnitude. It also follows from here that the initial amount of matter in the region of the giant planets (that is, σ_0) was several times greater than the amount entered into these planets. Therefore, the difficulty with the time scale for the formation of the outer planets proved surmountable (at least in the first approximation). Furthermore, the very discovery of this difficulty made it possible to discern an important, characteristic feature of the giant planet accumulation process: removal of bodies beyond the boundaries of the planetary system. Since they are not only removed from the solar system, but also to its outer region primarily, a source of bodies was thereby discovered which formed the cometary cloud.

The basic possibility of runaway growth, that is "runaway" in terms of the mass of the largest body from the general distribution of the mass of the remaining bodies in its feeding zone, has been demonstrated (Safronov 1969). Collisional cross-sections of the largest gravitating bodies are proportional to the fourth degree of their radii. Therefore, the ratio of the masses of the first largest body m (planet "embryo") to the mass m_1 of the second largest body, which is located in the feeding zone of m , increases with time. An upper limit for this ratio was found for the case of $\Theta = \text{const}$: $\lim(m/m_1) \approx (2\Theta)^3$.

An independent estimate of m/m_1 based on the present inclinations of the planetary rotation axes (naturally considered as the result of large bodies falling at the final stage of accumulation) was in agreement with this maximum ratio with the values $\Theta \approx 3 \div 5$.

These results were a first approximation and, naturally, required further in-depth analysis. Several years later, workers began to critically review the results from opposing positions. Levin (1978) drew attention to the fact that as a runaway m occurred, parameter Θ must increase. The ratio m/m_1 will correspondingly increase. Assuming m_1 and not m is an effective perturbing body in expression (3), he concluded that the ratio m/m_1 may have unlimited growth. Another conclusion was reached in a model of many planet embryos (Safronov and Ruzmaikina 1978; Vityazev *et al.* 1978; Pechernikova and Vityazev 1979). At an early stage all the bodies were small. The zones of gravitational influence and feeding of the largest

bodies, proportional to their radii, were narrow. Each zone had its own leader (a potential planet embryo) and there were many such embryos in the entire zone of the planet (with the total mass m_p): $N_e \sim (m_p/m)^{1/3}$ for low values of Θ and several times greater when Θ was high. Leaders with no overlapping feeding zones were in relatively similar conditions. Their runaway growth in relation to the remaining bodies in their own zones was not runaway in relation to each other. There was only a slight difference in growth rates that was related to the change of σ/P with the distances from the Sun. This difference brought about variation in the masses of two adjacent embryos in the terrestrial planet region $m/m_1 \sim 1 + 2m/m_p$. As the leaders grew, their ring zones widened, adjacent zones overlapped, adjacent leaders appeared in the same zone and the largest of them began to grow faster than the smaller one which had ceased being the leader. Masses of the leader grew, but their number was decreased. Normal bodies, lagging far behind the leader in terms of mass, and former leaders m_1, m_2, \dots , the largest of which had masses of $\sim 10^{-1}m$, were located in the zone of each leader m . Consequently, there was no substantial gap in the mass distribution of bodies. If the bulk of the mass in this distribution had been concentrated in the larger bodies, for example, if it had been compatible with the power law (4) with the exponent $q < 2$, the relative velocities of bodies could have been written in the form (2), with values of Θ within the first 10. The leaders in this model comprised a fraction μ_e of all the matter in the planet's zone, which for low values of Θ is equal to

$$\mu_e = N_e m / m_p \approx (m/m_p)^{2/3}, \quad (6)$$

while for large values of Θ , it is several times greater. Approximately the same mass is contained in former leaders. At the early stages of accumulation $m \ll m_p$ and $\mu_e \ll 1$. Thus, velocities of bodies are not controlled by leaders and former leaders, but by all the remaining bodies and are highly dependent upon the mass distribution of these bodies. In the case of the power law (4) with $q < 2$, runaway embryo growth leads only to a moderate increase in Θ to $\Theta_{max} \sim 10 \div 20$ at $M_e \sim 10^{-1}$, when control of velocities begins to be shifted to the embryos and Θ decreases to $1 \div 2$ at the end of accumulation (Safronov 1982). However, it has not proven possible, without numerical simulation of the process which takes into account main physical factors, to find the mass distribution that is established during the accumulation.

The first model calculation of the coupled evolution of the mass and velocity distributions of bodies at the early stage of accumulation (Greenberg *et al.* 1978) already led to interesting results. The authors found that the system, originally consisting of identical, kilometer-sized bodies, did not produce a steady-state mass distribution, like the inverse

power law with $q < 2$. Only several large bodies with $r \sim 200$ kilometers had formed in it within a brief time scale ($2 \cdot 10^4$ years.), while the predominate mass of matter continued to be held in small bodies. Therefore, velocities of bodies also remained low. Hence, Θ and not v increased in expression (2) as m increased. The algorithm did not allow for further extension of the calculations. If we approximate the mass distribution contained in Graph 4 of this paper by the power law (this is possible with $r > 5$ kilometers), we easily find that the indicator q decreases over time from $q \gtrsim 10$ where $t = 15,000$ years to ≈ 3.5 where $t = 22,000$ years. It can be expected that further evolution of the system leads to $q < 2$.

Lissauer (1987) and Artymovich (1987) later considered the possibility of rapid protoplanet growth (of the largest body) at very low velocities of the surrounding bodies. The basic idea behind their research was the rapid accretion by a protoplanet m of bodies in its zone of gravitational influence. The width of this zone $\Delta R_g = kr_H$ is equal to several Hills sphere radii $r_H = (m/3M_\odot)^{1/3}R$. As m increases, zone ΔR_g expands and new bodies appear in it, which, according to the hypothesis, had virtually been in circular orbits prior to this. According to Artymovich, under the impact of perturbations of m , these bodies acquire the same random velocities as the remaining bodies of the zone of m over a time scale of approximately 20 synodical orbital periods. Assuming that any body entering the Hills sphere of m , falls onto m (or is forever entrapped in this sphere, for example, by a massive atmosphere or satellite swarm, and only then falls onto m), Artymovich obtains a very rapid runaway growth of m until the depletion of matter in zone ΔR_g within $3 \cdot 10^4$ years in Earth's zone and $4 \cdot 10^5$ years in Neptune's zone. Subsequent slow increase of ΔR_g and growth of m occurs as a result of the increase in the eccentricity of the orbit of m owing to perturbations of adjacent protoplanets. Lissauer estimates the growth rate of m using the usual formula (1). Assuming random velocities of bodies until their encounters with a protoplanet to be extremely low, he assumes that after the encounter they approximate the difference of Kepler circular velocities at a distance of $\Delta R = r_H$. That is, they are proportional to $R^{-1/2}$. From this he obtains $\Theta_{eff} \propto R$. Assuming further that these rates are equal to the escape velocity from m at a distance of r_H , he finds for $R = 1$ AU $v/v_e = (r/r_H)^{1/2} \approx 1/15$, where $v_e = (2Gm/r)^{1/2}$, and he produces the "upper limit" of $\Theta_{eff} \approx 400$ for this value of v/v_e using data from numerical integration (Wetherill and Cox 1985). To generalize the numerical results to varying R 's, he proposes the expression

$$\Theta_{eff} \sim 400 R_{ae} (\delta/4)^{1/3}, \quad (7)$$

for a "maximum effective accretion cross-section" at the earliest stage of

accumulation, where R_{ae} denotes the distance from the Sun in astronomical units.

This approach has sparked great interest. First of all, it makes it possible to reconcile rapid accumulation with runaway of large bodies in computations relating to the early stage with slow accumulation in computations for the final stage. Runaway growth in the Earth's zone ends with m on the order of several lunar masses; in Jupiter's zone it is about ten Earth masses (within a time scale of less than 10^6 years). Secondly, an increase in Θ with a distance $\propto R$ from the Sun significantly accelerates the growth of giant planets and may help in removing difficulties stemming from the length of their formation process. Therefore, we need more detailed consideration of the plausibility of the initial assumptions of this work, and an assessment of the role of factors which were not taken into account, namely, the overlapping of ΔR_g zones of adjacent protoplanets and the encounters of bodies with more than one of these and repeated encounters of bodies with a protoplanet and collisions between bodies. This would allow an estimation of the extent to which the actual values of Θ may differ from Lissauer's value for Θ_{eff} , qualified by himself as the maximum value.

The idea of runaway planet growth has not been confirmed in several other studies. These include, for example, numerical simulation by Lecar and Aarseth (1986), Ipatov (1988), Hayakawa and Mizutani (1988), and analytical estimates by Pechernikova and Vityazev (1979). Wetherill notes that the runaway growth obtained by Greenberg *et al.* (1978) is related to defects in the computation program. Nevertheless, he feels that runaway growth may stem from other, as yet unaccounted factors. The first of these is the tendency toward an equiportion of energy of bodies of varying masses, which reduces velocity of the largest bodies and leads to acceleration of their growth (1990, in this volume).

Stevenson and Lunine (1988) recently proposed a mechanism for the volatile compound enrichment of the Jovian zone (primarily H_2O) as a result of turbulent transport of volatiles together with solar nebula gas from the region of the terrestrial planets. Vapor condensation in the narrow band of $\Delta R \approx 0.4$ AU at a distance of $R \approx 5$ AU may increase the surface density of solid matter (primarily ices) in it by an order of magnitude and significantly speed up the growth of bodies at an early stage. Using Lissauer's model of runaway growth, the authors have found a time scale of of $\sim 10^5 \div 10^6$ years for Jupiter's formation.

The possibility of the acceleration of Jupiter's growth by virtue of this mechanism is extremely tempting and merits further detailed study. At the same time, complications may also arise. If, for example, not one, but several large bodies of comparable size are formed in a dense ring, their mutual gravitational perturbations will increase velocities of bodies, the ring will expand, and accumulation will slow down. In view of this reasoning,

it must be noted that the question of the role of runaway growth in planet formation cannot be considered resolved, despite the great progress achieved in accumulation theory. It is, therefore, worthwhile to consider how the existence of asteroids and comets constrains the process.

CONDITIONS OF ASTEROID FORMATION

It is now widely recognized that there have never been normal-sized planets in the asteroid zone. Schmidt (1954) was convinced that the growth of preplanetary bodies in this zone originally occurred in the same way as in other zones, but was interrupted at a rather early stage because of its proximity to massive Jupiter. Jupiter had succeeded in growing earlier and its gravitational perturbations increased the relative velocities of the asteroid bodies. As a result, the process by which bodies merged in collisions was superseded by an inverse process: their destruction and breakdown. It was later found that Jovian perturbations may increase velocities and even expel asteroids from the outermost edge of the belt $R > 3.5$ AU, and resonance asteroids from "Kirkwood gaps," whose periods are commensurate with Jupiter's period of revolution around the Sun. The gaps are extremely narrow, while the mass of all of the asteroids is only one thousandth of the Earth's mass. Therefore, removal of 99.9% of the mass of primary matter from the asteroid zone is a more complex problem than the increase of relative velocities of the remaining asteroids, (up to five kilometers per second, on the average).

A higher density of solid matter in the Jovian zone, due to condensation of volatiles, triggered a more rapid growth of bodies in the zone, and correspondingly, the growth of random velocities of bodies and eccentricities of their orbits. With masses of the largest bodies $> 10^{27}$ g, the smaller bodies of the Jovian zone (JZB) began penetrating the asteroid zone (AZ) and "sweeping out" all the asteroidal bodies which stood in its way and were of significantly smaller size. It has been suggested that the bulk of bodies was removed from the asteroid zone in this way (Safronov 1969). Subsequent estimates have shown that the JZB could only have removed about one half of the initial mass of AZ matter (Safronov 1979). In 1973, Cameron and Pine proposed a resonance mechanism by which resonances scan the AZ during the dissipation of gas from solar nebulae. However, it was demonstrated (Torbett and Smoluchowski 1980) that for this to be true, a lost mass of gas must have exceeded the mass of the Sun. In a model of low-mass solar nebulae ($\lesssim 0.1M_{\odot}$), resonance displacement could have been more effective as Jupiter's distance from the Sun varied both during its accretion of gas and its removal of bodies from the solar system.

We can make a comparison of the growth rates of asteroids and JZB using (1), if we express it as

$$\frac{dr_a}{dr_j} = \frac{(1 + 2\Theta_a)\sigma_a\delta_j}{(1 + 2\Theta_j)\sigma_j\delta_a} \left(\frac{R_j}{R_a}\right)^{3/2}, \quad (8)$$

where the indices a and j , respectively, denote the zones under consideration. Assuming $\Theta_j \approx 2\Theta_a$, $\delta_j \approx 2\delta_a/3$, $\sigma_j/\sigma_a \approx 3(R_j/R_a)^{-n}$, that is, a threefold density increase in the Jovian zone due to the condensation of volatiles, we have $dr_a/dr_j \approx (R_j/R_a)^{3/2+n}/9 \approx 0.1 \cdot 2^{3/2+n}$. It is clear from this that the generally accepted value for the density $\sigma g(R)$ of a gaseous solar nebula of $n = 3/2$ yields $dr_a \approx dr_j$, that is, it does not cause asteroid growth to lag behind JZB. In order for JZB's to have effectively swept bodies out of the AZ, there would have to have been a slower drop of $\sigma g(R)$ with $n \approx 1/2$ (Ruzmaikin *et al.* 1989) and, correspondingly, for solid matter $\sigma_j \approx 15 \div 20 \text{ g/cm}^2$. This condition is conserved when there is runaway growth of the largest bodies in both zones. Expression (8) is now formulated not for the largest, but for the second largest bodies. The ratio $\Theta_j \approx 2\Theta_a$ is conserved. However, a large body rapidly grows in the asteroidal zone, creating the problem of how it is to be removed. The second condition for effective AZ purging is the timely appearance of JZB's in it. Eccentricities of their orbits must increase to $0.3 - 0.4$, while random velocities of $v \approx ewR$ must rise to two to three kilometers per second. According to (2), the mass of Jupiter's "embryo" must have increased to a value of $m'_j \approx m_\oplus(0.1\Theta)^{3/2}$. It is clear from this that JZB penetrating the asteroidal zone at the stage of rapid runaway growth of Jupiter's core, according to Lissauer, (with $\Theta_{eff} \approx 10^3$ to $m_c \approx 15m_\oplus$) is ruled out entirely. In view of these considerations, the values of $\Theta_j \lesssim 20 \div 30$ and $\Theta_a \lesssim 10 \div 15$ are more preferable. But the time scale for the growth of Jupiter's core to its accretion of gas then reaches 10^7 years.

THE REMOVAL OF BODIES FROM THE SOLAR SYSTEM AND THE FORMATION OF THE COMETARY CLOUD

Large masses of giant planets inevitably lead to high velocities of bodies at the final stage of accumulation and, consequently, to the removal of bodies from the solar system at this stage. It follows from this that the initial mass of solid matter in the region of giant planets was significantly greater than the mass which these planets now contain. It also follows that part of the ejecta remained on the outskirts of the solar system and formed the cloud of comets. The condition, that the total angular momentum of all matter be conserved, imposes a constraint upon the expelled mass ($\sim 10^2 m_\oplus$). Since the overwhelming majority of comets unquestionably belongs to the solar system and could not have been captured from outside, and since *in situ* comet formation at distances of more than 100 AU from the

Sun are only possible with an unacceptably large mass of the solar nebula, the removal of bodies by giant planets appears to be a more realistic way of forming a comet cloud. The condition for this removal is of the same kind as the condition for the ejection of bodies into the asteroidal zone. It is more stringent for Jupiter: velocities of bodies must be twice as great. For the outer planets, the ejection condition can be expressed as $m_p/m_\oplus > 4 (\Theta/R_{ae})^{3/2}$. It follows from this that Neptune's removal of bodies is only possible where $\Theta < 10^2$; for Uranus it is only possible for an even lower Θ .

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